On the Performance of Space Shift Keying for Optical Wireless Communications

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Abstract—**In this paper, we study the performance of Space Shift Keying (SSK) modulation applied to optical wireless channels. The optical Multiple-Input-Single-Output (MISO) channel used here is obtained through measurements. The experimental setup consists of two lasers and an optical receiver. Using the channel measurements, the performance of SSK is compared to the Single-Input-Single-Output (SISO) transmission case. We build upon a recent finding, obtained for a two-transmitter case, that power imbalance at the transmitters can enhance the performance of SSK, especially in highly correlated channels [1]. It is found in this paper that SSK applied to real optical wireless channels outperforms SISO and Single-Input-Multiple-Output (SIMO) transmission if more than four optical transmitters are used. Furthermore, we show that Space Shift Keying can also exceed Multiple-Input-Multiple-Output (MIMO) setups which apply repetition coding as SSK exploits receive-diversity in a better way.**

I. Introduction

The ever increasing demand for higher data rates in wireless systems makes radio frequency (RF) spectrum a precious commodity. In fact, the available bandwidth constitutes a limiting factor for achieving higher transmission rates. In sharp contrast, the spectrum in the range of visible or infra-red light offers almost limitless bandwidth and with the advent of high power light emitting diodes (LEDs) powerful and, at the same time, cheap transmitters exist. Therefore, optical wireless communications (OWC) can mature into a promising complement to RF based systems since it could potentially offload a significant amount of traffic in indoor environments from the RF domain to the optical wireless domain resulting in a noticeable RF spectrum relief.

The parallel usage of multiple transmitters and receivers in wireless RF communications can enhance the overall system performance [2], [3]. These so called Multiple-Input-Multiple-Output (MIMO) methods increase the spectral efficiency and can reduce the bit error ratio (BER) of a communication system. For instance, the Bell Laboratories layered space-time (BLAST) architecture [4] and the Alamouti scheme [5] are two well-known MIMO techniques. But as these techniques couple multiple transmission symbols in time and space by simultaneously sending them from all transmit antennas, they cause inter-channel interference (ICI). Therefore, these MIMO implementations require sophisticated detection or pre-coding algorithms which lead to high receiver or transmitter intricacy and considerable system complexity.

Recently, Spatial Modulation (SM) [6] and particularly its low complexity implementation Space Shift Keying (SSK) [7] have been proposed as promising solutions to reduce the high intricacy of MIMO systems. This is due to the fact that SM and SSK completely avoid ICI in time and space. Furthermore, these two techniques can operate with any number of receive antennas in comparison to e.g. BLAST, which requires at least as many receive antennas as transmit antennas. The basic principle of SSK is that it considers the transmitter array as a spatial constellation diagram leading to spatially encoded bits. Thus, information to be transmitted resides in the physical location of the transmitter (the transmitter index). As only one transmit antenna is active at any time instant and all others emit zero power at that time, ICI is completely avoided. The SSK receiver employs a specific detection process which identifies the transmitter that has emitted power. Results presented in [6]-[8] have demonstrated the potential and the reduced computational complexity of SM and of SSK. It has been shown that SSK can work properly even in correlated channels with power imbalance and that it exploits receive-diversity in a better way compared to common Single-Input-Multiple-Output (SIMO) setups. Besides, [9] and [10] show that SM and SSK can also be combined with Orthogonal Frequency Division Multiplexing (OFDM) transmission to enhance spectral efficiency and to cope with severe channel conditions like frequency-selective fading.

Because of its simplicity and its characteristics, Space Shift Keying seems to be a proper modulation technique for low-complex optical wireless communications. This is due to the fact that SSK is based on mere signal pulses i.e. the phase of the transmission signal is not used for conveying information. Therefore, it is especially appropriate for OWC which employs incoherent light sources and uses intensity modulation at the transmitter and direct detection at the receiver side [11]. Intensity modulation and direct detection offer easy implementation and therefore promote low-cost optical modulation and demodulation equipment [12]. But this simplicity is gained at the expense of losing the optical carrier's frequency and phase information. Thus, common RF modulation techniques cannot be directly applied to optical communications and specific new approaches have to be developed.

Due to its appropriateness and its promising potential for OWC [13], we will study in this paper the performance of SSK modulation in an actual optical wireless propagation environment. In order to evaluate its performance, we will compare SSK to Single-Input-Single-Output (SISO) and SIMO transmission which employ the same power and spectral efficiency. Additionally, SSK is compared to MIMO scenarios which apply repetition coding as these achieve very good performance in optical wireless communications [14]. Furthermore, we will study the effect of transmit power imbalance, which is analysed in [1], where it is found that power imbalance can enhance the performance of SSK in highly correlated channels.

The remainder of this paper is organised as follows: In Section II, we introduce the basic Space Shift Keying system model. Section III describes the optical wireless test setup which is used for real time measurements to derive the optical wireless channel used in this paper. In Section IV, the performance of SSK is studied. Finally, Section V concludes the paper.

II. Space Shift Keying System Model

Notation: The following notations are used throughout the entire paper: bold symbols denote vectors. We use $(\cdot)^T$ for the transpose operator and $|\cdot|$ for the absolute value of a scalar. $\mathrm{E}\{\cdot\}$ stands for the expectation operator and $\mathrm{VAR}\{\cdot\}$ for the standard deviation.

Generally, a $N_t \times N_r$ MIMO system consists of N_t transmit and N_r receive devices. In the following, we consider a basic Multiple-Input-Single-Output (MISO) setup with $N_t = 2$ transmit devices and one receiver ($N_r = 1$). Channel coding is not taken into account within this paper.

By using Space Shift Keying modulation, a random bit sequence is passed to the SSK encoder. The encoder maps the input bits to a constellation vector $\mathbf{x} = [x_1\ x_2]^T$, where the index specifies the respective transmitter. At any given time instance, only one of the two transmitters radiates optical power. Which one is exactly active depends on the random bit sequence at the encoder input. The received signal is given by

$$y = \mathbf{hx} + n, \tag{1}$$

where $\mathbf{h} = [h_1\ h_2]$ represents the transfer factors of the wireless 2×1 channel. Besides, n is the noise, which we assume as additive white Gaussian noise (AWGN) with zero mean and of power N_0, affecting the average signal to noise ratio (SNR) at the receiver. At the receiver, perfect knowledge of the channel and ideal time synchronisation is assumed. The detection is based on the Maximum-Likelihood (ML) principle meaning that the detector decides for the constellation vector $\widehat{\mathbf{x}}$ which minimises the Euclidean distance between the actual received signal y and all potential received signals leading to

$$\widehat{\mathbf{x}} = \arg\max_{\mathbf{x}} p_y(y|\mathbf{x},\mathbf{h}) = \arg\min_{\mathbf{x}} |y - \mathbf{hx}|^2, \tag{2}$$

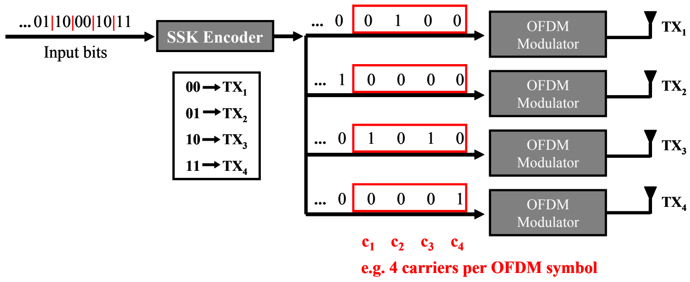

Fig. 1. Illustration of SSK in combination with OFDM.

where p_y is the probability density function of y conditioned on $\mathbf{x}$ and $\mathbf{h}$. Therefore, by applying SSK demodulation, the receiver has to estimate the index of the respective transmit device (e.g. laser or LED) which is active in order to decode the bit sequence generated at the transmitter side.

As shown in [9], Space Shift Keying can also be combined with OFDM. Fig. 1 illustrates this combination for an exemplary setup using $N_t = 4$ transmitters. Hence, SSK is individually applied to each single subcarrier in the frequency domain. Therefore, each subcarrier is mapped to one of the optical transmitters and the respective other transmitters emit zero power on this frequency. By doing so, the output of the SSK encoder delivers a specific set of subcarriers for each transmit device to which a OFDM modulator (Inverse Fast Fourier Transformation) is separately applied. In order to generate real valued signals after the OFDM modulator, Hermitian symmetry of the modulator input is enforced. This generates specific intensity modulated signals which are emitted by each optical transmitter and which contain the distinctive SSK modulated data bits. Through this we achieve several parallel SSK transmissions in the frequency domain. Because of the narrow bandwidth of the single OFDM subcarriers, each one of them can be regarded as a self-contained fading channel with its own characteristics $\mathbf{h}$. At the receiver side, the sum signal y is processed by an OFDM demodulator and the SSK modulated data bits are separately decoded for each subcarrier by using the Maximum-Likelihood principle in (2).

III. Optical Wireless Test Setup

In the following, we describe the test setup which is employed to measure the optical wireless channel and to obtain the transfer factors $\mathbf{h}$, which are used in the simulations presented in Section IV-A. The setup comprises two optical transmit devices (TX_1 and TX_2), which are two identical laser installations using a red laser diode with a wavelength of 658 nm. The optical receiver (RX) consists of a circuitry applying a BPX65 Silicon PIN (Positive Intrinsic Negative) photo diode. As Fig. 2 illustrates, both transmitters have a direct line of sight link to the optical receiver at which the distance of TX_2 to RX (displayed as d_2) is 60 cm and TX_1 is about 70 cm away from the receiver. The distance d_1 between TX_1 and TX_2 is 30 cm. As illustrated, the angle of incidence of the laser beam from TX_1 on the optical receiver is 45°,

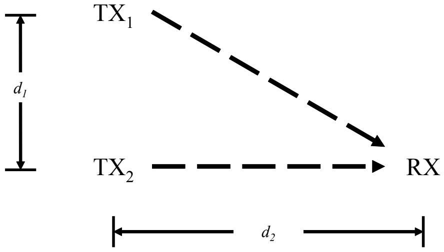

Fig. 2. Illustration of the optical wireless test setup.

whereas the beam of TX_2 directly reaches the photo detector without an angular misalignment.

Fig. 3 displays the average measured gains of the optical wireless links between both transmitters and the receiver. Within this setup, we use Space Shift Keying modulation in combination with OFDM. Thus, the gains are plotted over a frequency range of 8 MHz consisting of 80 measured subcarriers with a spacing of 100 kHz. The displayed gains are averaged over 50 independent series of measurements. It can be seen that the transmission link between TX_1 and RX undergoes a channel attenuation which is about 2.7 dB higher in comparison to the transmission between TX_2 and the optical receiver. As both lasers use the same transmission power, this deficit is caused by the misaligned angle of incidence of TX_1 leading to less received power at the photo diode and a power imbalance between both links. Furthermore, it can be seen that both transmission links are highly correlated leading to a time averaged correlation coefficient of about

$$\rho(h_1, h_2) = \frac{\text{E}\left\{(h_1 - \text{E}\left\{h_1\right\})(h_2 - \text{E}\left\{h_2\right\})\right\}}{\sqrt{\text{VAR}\left\{h_1\right\} \text{VAR}\left\{h_2\right\}}} = 0.93.$$

IV. Results

In this section, we analyse the performance of Space Shift Keying modulation for the measured optical channel samples and for an enhanced $N_t \times N_r$ setup. SSK is compared to SISO, SIMO and MIMO transmissions which use simple on-off-keying (OOK) or pulse amplitude modulation (PAM). M-PAM is an extension of OOK by using a set of M scaling factors for intensity modulation of the optical carrier instead of using only two factors (on and off). In order to ensure comparability, all considered schemes (SSK, SISO, SIMO and MIMO) use the same overall transmission power E_s and provide equal spectral efficiency by transmitting the same number of bits per channel use. Furthermore, Ω_i is the power imbalance in dB between the transmit devices, where the index i displays which transmitter utilises the power surplus (note that in this scenario the overall transmission power is still E_s).

A. SSK in measured optical wireless channels

First of all, we examine the performance of SSK for the measured optical wireless channels with power balance of both optical transmitters i.e. $\Omega_1 = \Omega_2 = 0$. As displayed in Fig. 4, there is a close matching between our ascertained bit error ratio performance of SSK and the analytical average bit error probability (ABEP) for two transmitters reported in [1] which is ABEP = $\text{E}\left\{\text{P}_\text{E}(\mathbf{h}_1, \mathbf{h}_2)\right\}$, where

$$\text{E}\left\{\text{P}_\text{E}(\mathbf{h}_1, \mathbf{h}_2)\right\} = \text{E}\left\{Q\left(\sqrt{\overline{\gamma}\sum_{n=1}^{N_r}|h_{2,n} - h_{1,n}|^2}\right)\right\}. \quad (3)$$

$\text{P}_\text{E}(\cdot,\cdot)$ is the probability of detecting the wrong transmitter index at the receiver, when conditioning upon the channel transfer factors $\mathbf{h}_1 = [h_{1,1}\ h_{1,2}\ \ldots\ h_{1,N_r}]$ and $\mathbf{h}_2 = [h_{2,1}\ h_{2,2}\ \ldots\ h_{2,N_r}]$ of the links between the two transmitters and the N_r receivers. In our experimental setup $N_r = 1$. $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp(\frac{-t^2}{2})\ dt$ is the Q-function and $\overline{\gamma} = \frac{E_s}{4N_0}$. In comparison to the OOK transmission for TX_1 and TX_2, SSK exhibits a larger BER in this scenario because of the high correlation of both channels.

Fig. 5 presents the effect of power imbalance on the optical wireless test setup. It can be seen that if $\Omega_1 = 3$, the performance of SSK decreases. This is due to the fact that the attenuation of both channels differs of about 3 dB. Thus, by granting TX_1 a power surplus of 3 dB, the difference between

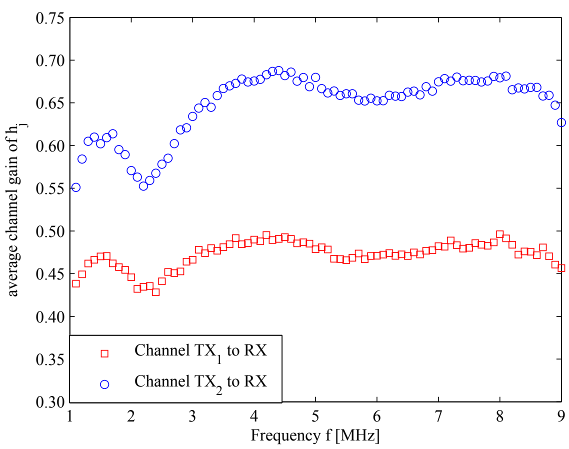

Fig. 3. Measured gains of the optical wireless channels.

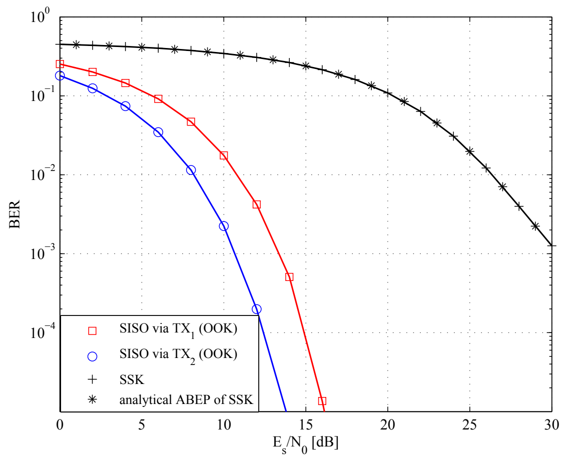

Fig. 4. BER against E_s/N_0 for the measured optical wireless channels with power balance ($\Omega_1 = \Omega_2 = 0$) for 1 bit transmission.

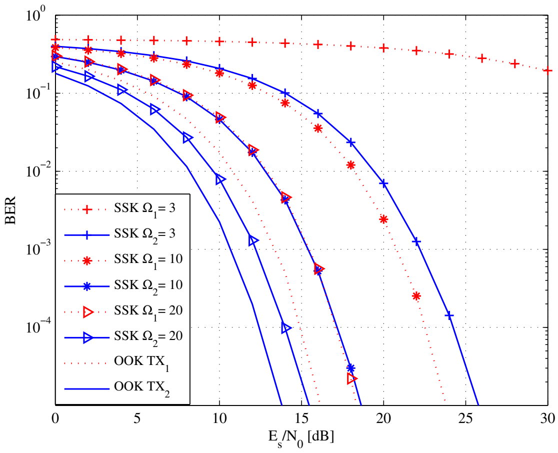

Fig. 5. BER against E_s/N_0 for the measured optical wireless channels with different power imbalance (1 bit transmission).

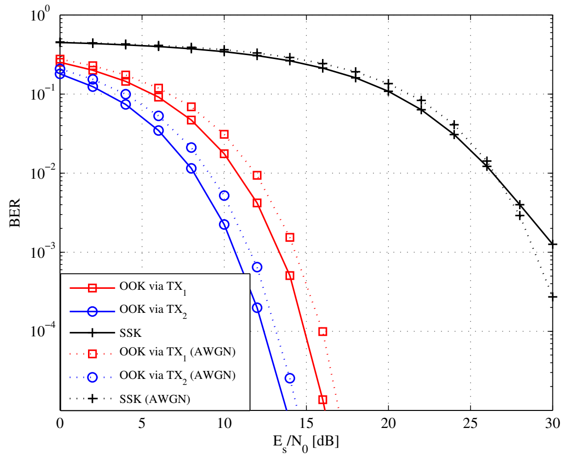

Fig. 6. Comparison of BER against E_s/N_0 for the measured optical wireless channels and for the AWGN case with constant channel attenuations $h_1 = 0.48$ and $h_2 = 0.65$ (1 bit transmission).

both channels gets even less and their unique characteristic is balanced. If applying other scenarios for Ω_1 and Ω_2, the performance of SSK steadily enhances with rising Ω_i as the difference between both channels increases making them more distinguishable, while the overall transmitted power E_s remains constant. The upper bound of the performance of SSK is the OOK scenario, where the power imbalance is maximum.

B. SSK in AWGN scenario

The measurement results of the optical channel obtained by the experimental test setup show only little variations across the single subcarriers and across time. Therefore, the channel can be assumed as a flat AWGN channel with constant attenuation. In order to evaluate this assumption, we consider in the following an AWGN channel with constant attenuation for our 2×1 optical wireless test setup. By doing so, the attenuations of the two links are set to the mean of the measured channel gains displayed in Fig. 3. Thus, the transmission link between TX_1 and RX undergoes a channel attenuation of $h_1 \approx 0.48$, whereas the transmission link between TX_2 and the optical receiver has a channel attenuation of $h_2 \approx 0.65$. This leads to a power imbalance between both links. Fig. 6 displays the comparison of the measured optical wireless channels and of the mere AWGN case with the constant channel attenuations h_1 and h_2. As both results show a good match, the AWGN scenario with constant channel gain is a good approximation for the analysed 2×1 setup with direct line of sight between the two transmitters and the optical receiver.

C. SSK in an enhanced $N_t \times N_r$ setup

As shown, SSK cannot achieve gains in a simple 2×1 setup. Thus, in the following we analyse its performance in an enhanced $N_t \times N_r$ setup with several optical transmitters and receivers. By doing so, we compare SSK to SIMO and MIMO transmissions, which use the same number of optical transmitters/ receivers and equal mean transmission power E_s. Due to comparability regarding the amount of bits sent, we compare SSK to M-PAM transmission. Since Space Shift Keying conveys $m = \log_2(N_t)$ bits per channel use and for M-PAM $m = \log_2(M)$, both techniques have the same spectral efficiency if $M = N_t$. For the following M-PAM MIMO scenarios, repetition coding is used where the same PAM-signal is simultaneously emitted from the N_t optical transmitters. In [14] it is shown that for OWC, repetition coding outperforms SIMO setups because of transmit-diversity. This is due to the fact that the optical intensities coming from sufficiently separated transmitters are orthogonally detected by the receivers. Therefore, the repetition coding scheme combines the faded signals before any noise accumulation unlike a SIMO scheme which combines the noisy faded signals. Thus, we compare SSK to these MIMO setups which apply repetition coding whereas ideal time synchronisation between the single MIMO paths is assumed.

Based on the results of Section IV-B, we use in the following AWGN channels with different gains for the wireless links between the transmitters and receivers. The channel gains are assumed to be independent values drawn from a uniform distribution on the unit interval. By doing so, the single channel links experience power imbalances between each other due to different attenuations like in the optical test setup. Fig. 7 presents the simulation results of a system setup with $N_t = 4$ transmitters and several receivers. All schemes transmit 2 bits in this scenario. Although SIMO and MIMO still perform better, it can be seen that SSK benefits from the enhanced number of transmit and receive devices. Especially with rising number of optical receivers, SSK can exploit the receive-diversity in a better way than SIMO and MIMO as the performance gap decreases. Fig. 8 and Fig. 9 show that SSK outperforms SIMO transmission in a setup employing $N_t = 8$ and $N_t = 16$ transmitters even if $N_r < N_t$. In comparison to repetition coding, SSK can outperform the MIMO scheme within a SNR range of about 10 - 27 dB if $N_t = 8$. At higher SNRs, the gain of repetition coding comes into play and makes it superior. In a $N_t = 16$ setup, SSK performs best and it can be seen that repetition coding has no benefits even compared

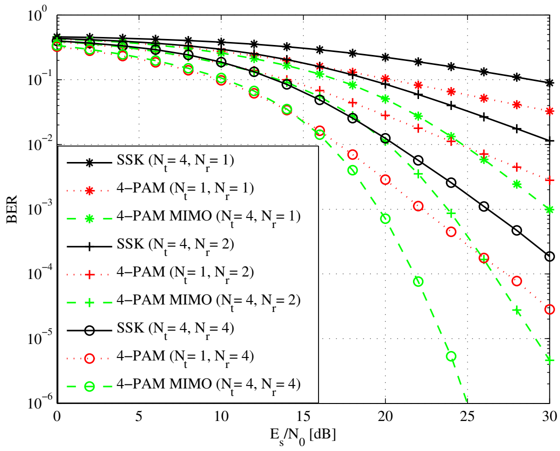

Fig. 7. BER against E_s/N_0 for AWGN scenario (2 bits transmission).

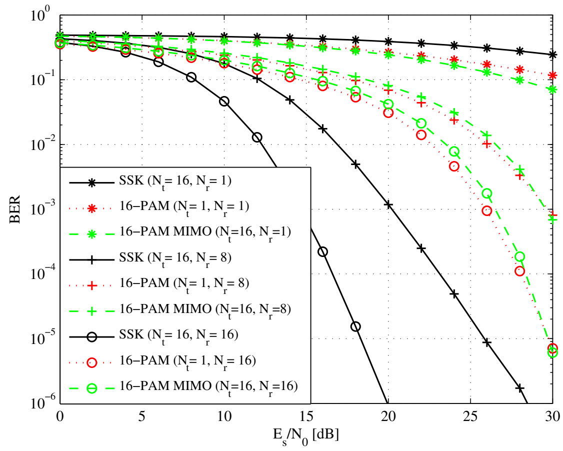

Fig. 9. BER against E_s/N_0 for AWGN scenario (4 bits transmission).

to SIMO transmission. The results show that more than four transmit devices have to be used in order to profit from SSKs potential and to achieve gains compared to SIMO and MIMO transmission. These gains increase with rising number of employed transmitters and receivers.

V. Summary and Conclusion

In this paper, we have studied the performance of Space Shift Keying modulation under optical wireless channel conditions, which have been obtained by actual channel measurements. SSK has been compared to SISO, SIMO and MIMO transmission scenarios. The results show that the performance of SSK modulation is strongly affected by the channel conditions and that simple 2×1 SSK cannot make use of transmit-diversity gains. Nevertheless, power imbalance on the different transmitters can enhance its performance, especially for highly correlated optical wireless channels with direct line of sight. Furthermore, we have shown that SSK can deploy its transmit-diversity potential and achieves benefits over SIMO and MIMO setups if more than four transmit devices are used. We have also illustrated that SSK can exploit receive-diversity in a better way. Future work will deal with further performance measurements of Space Shift Keying in an extended test setup using more than two optical transmitters and several receivers under real channel conditions.

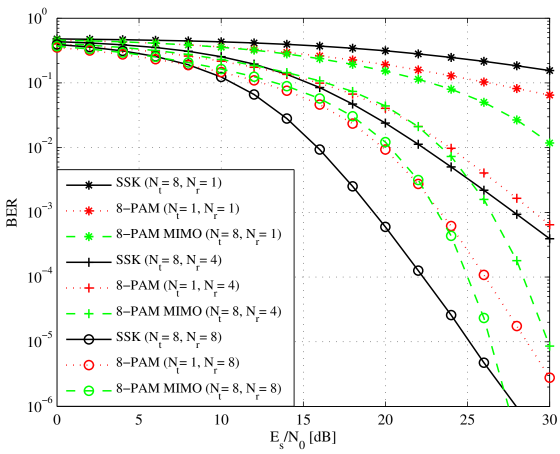

Fig. 8. BER against E_s/N_0 for AWGN scenario (3 bits transmission).

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